Comparison of energy simulations for a residential unit: a rapid method for an integrated decision tool

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Abstract

This work defines a methodology aimed at the creation of a simplified energy model able to simulate a residential building with a reasonable workload. The simulation results should have a sufficient accuracy at any stage of a building design, by exploiting the benefits of a modular approach with increasing detail rendition. The idea is to verify the accuracy of the simulations comparing different methodologies, from stationary simulations, using a Italian software called TERMUS, to more sophisticated, even if standard, dynamic simulations, using TRNSYS. Such comparisons have already been carried out in the past in different papers, but a thorough analysis of the envelope-plant system using progressive simplification steps has not yet been done, especially for a residential test case in an on-going retrofit process. The results indicate that with the proper simplification steps, shown in the analysis, the accuracy in terms of energy needs and power curves is very high (the difference with the most complete analysis is always below 12% for all the output parameters) with a workload of a few hours for the preparation of the model and the simulations. The fact of having considered a case in northern Italy does not limit the universality of the procedure, which may be applied for a very large number of built environments in residential areas.

1. Introduction

The daily operation of commercial and residential buildings comprises roughly one-third of the world’s primary energy consumption. Because buildings typically operate for many years, there is great potential for reducing global energy needs through improved building design (Urban et al., 2006).

Computer modelling and simulation are powerful technologies for addressing interacting architectural, mechanical, and civil engineering issues in buildings. Building Performance Simulations (BPS) can help to reduce emissions of greenhouse gases and to provide substantial improvements in fuel consumption and comfort levels, by treating buildings and their thermal systems as optimized entities, and not as the sum of a number of separately designed and optimized sub-systems or components (Hensen, 2004).

Experience with real buildings has shown that low-energy design is not intuitive and that simulations should therefore be an integral part of the design process (Torcellini et al., 1999; Hayter et al. 2001).

In fact, for energy saving components, an intuitive selection appears to have additional drawbacks: for example the efficiency of these components cannot be studied in isolation. They are dependent on building characteristics whereas interaction between components can have a substantial effect on the efficiency of each individual component. The impact of climate conditions and occupant behaviour adds to the complexity and makes it almost impossible to predict performance without use of computational tools (De Wilde et al., 2001).

However, architects and designers are still finding it difficult to use even basic tools (Punjabi et al., 2005). Findings confirm that most BPS tools are not compatible with architects’ working methods and needs (Attia et al., 2009; Gratia et al., 2002).

Needs related to the design process can be easily identified as time and accuracy. Accuracy is an essential prerequisite for every analysis used for decision-making and becomes significantly more relevant during the design process of buildings, where decisions taken can concern a large amount of energy and can affect the building for a large number of years. Accurate energy analysis requires time but this is in contrast with the necessity to minimize the time requirements to make it compatible with design times. A way to reduce time requirements could be the introduction of default values and databases for inputs, with the possible risk of reducing the model detail level and degree of freedom, themselves influencing the accuracy or relevance of the final result (Picco et al., 2013).

Considering the whole building-plant system, results from a stationary simulation are compared with different dynamic simulations characterized by gradually increasing simplifications both in terms of building envelope and plant. A very detailed model is simulated in order to define the reference case, in terms of building energy loads, power curves and the efficiency of all the subsystems belonging to the heating system. Differences between the detailed and the simplified models are analysed to determine the quality of the results of the latter.

2. Building Description

The case study under exam is a standard residential unit in a building built in 1989, situated in Bergamo, Italy. The use of such a test case was chosen due to the large number of residential buildings with such construction characteristics in the area of northern Italy. In future years, a great part of the energy retrofit will be carried out on such kinds of units and there is an important interest in offering low cost, but still accurate, dynamic simulations of such situations.

The building consists of three floors, the basement for the garage and winery, and the ground and first floors, each intended for residential purposes. In particular, as opposed to one on the first floor, the apartment on the ground floor is not currently used and needs a renovation in order to make it habitable.

Retrofit design and simulations focus just on this portion of the building, characterized by an usable floor area of 86.25 m^2, a total net volume of 232.88 m^3, 7 heated spaces/rooms and a central unheated stairwell necessary to connect the basement to the ground floor apartment (Figure 1).

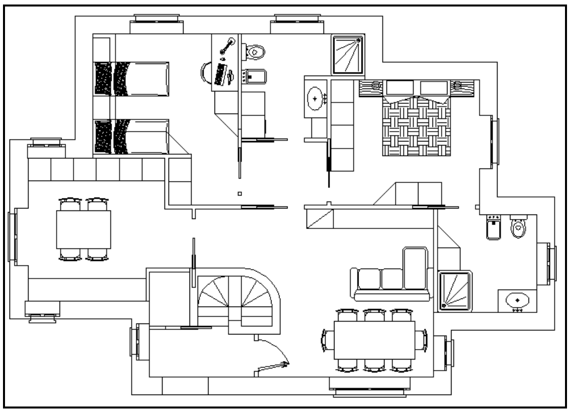

Figure 1 – Design of the interior layout of the apartment

Currently the building envelope, except the ceiling adjacent to the upper apartment, is only composed of the structural part made of reinforced concrete, and the renovation design provides to isolate the internal surface of 311 m^2 through wall and window stratigraphy, able to ensure both high energy performances and the access to the tax benefits expected for this kind of building work.

In particular, as provided by retrofit design, the opaque vertical surfaces will have a transmittance equal to 0.262 W/m^2K, while the floor adjacent to the basement will have a transmittance of 0.285 W/m^2K and for the 14.88 m^2 of transparent dispersants a global average transmittance of 1.5 W/m^2K is set for the simulations. The HVAC plant is expected to meet only the winter thermal load through a heating system composed of 7 aluminum radiators (one for each room) powered by a 5 kW condensing natural gas boiler.

A climate control for the supply temperature of the heating plant is provided, together with an internal regulation composed of thermostatic valves able to reduce or increase the flow rate of the heat transfer fluid to the radiators. The isolated distribution network piping will be placed inside the heated environments in order to reduce losses to a minimum value.

3. Stationary simulation

Once the key features of the building-plant system have been defined, a first stationary simulation was carried out using TERMUS software (produced by ACCA software S.p.a., M. Cianciulli road - 83048 Montella (AV), Italy - more information at www.acca.it).

The TERMUS model consists of a single thermal zone divided into 7 rooms and of all other heated areas (first floor apartment) and unheated spaces (basement, stairwell and the boiler room) necessary to determine, with monthly time-steps, the average temperatures of all the surfaces (Figure 2).

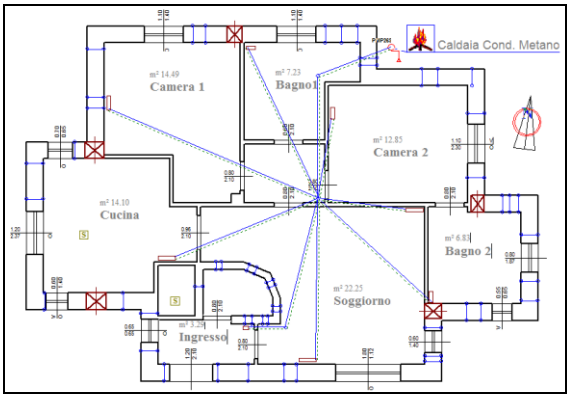

Figure 2 – TERMUS simulation model and heating plant design

The wall stratigraphy of the model consists of 22 different types identified with 15 different materials. A basic time schedule for the heating system has been defined as input and the following quantities have been estimated:

- Losses related to thermal bridges;
- Geometric shadowing objects and obstruction due to the building and its urban context;
- Standard values for infiltration and internal contributions (values recommended by current legislation);
- Standard values of efficiency for the emission, regulation, distribution and generation subsystems (even for these, the software considers values recommended by current legislation);

The software generates as main output results the following parameters:

- Maximum thermal power required from each room in the design conditions (kW);
- Monthly thermal energy demand of the whole zone simulated (kWh);
- Monthly Primary energy demand of the entire simulated zone (kWh);

Then, based on the first output described, it proceeds to the heating plant design, sizing the components and verifying their operation in the maximum load condition (Figure 2).

The software does not consider the possible presence of a storage tank and does not take into account the recovery of the potential distribution losses.

4. Dynamic Simulations

As a second step, a complete dynamic energy simulation of the entire building-plant system was performed through the TRNSYS software. This complete model was subjected to a series of simplifications both for the building envelope and for the plant, in order to determine deviations and therefore quality of the results of the simplified models.

4.1 Detailed model

In terms of building envelope, as seen for the stationary simulation, the model consists of seven homogenous thermal zones, fully describing all conditioned rooms, underground non-conditioned space, and all accessory non-conditioned volumes like the stairwell, boiler room and attic.

Through the specific Trnsys3D tool, the three-dimensional modeling of the entire building was created, as well as all relevant shadowing objects comprising all the adjacent building structures and the specific solar obstructions (Figure 3).

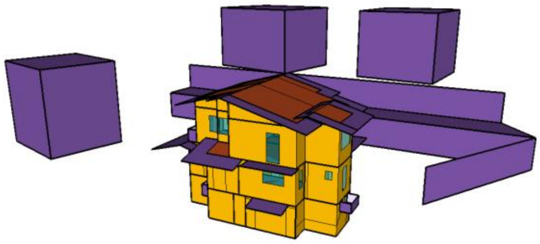

Figure 3 – Complete model for building envelope (Trnsys3D)

To characterize the various zones, each one defined in terms of materials and stratigraphy of walls and windows, thermal bridges, internal gains, temperature set-points and time heating schedule, the same data of the previous stationary simulation were used, adding all parameters not considered by this kind of design, as the heat capacity of the materials or external and boundary conditions with hourly rather than monthly time-step.

This characterization was achieved by TRNBuild tool, the Trnsys software tool specifically dedicated to the characterization of the building envelope.

Finally, in order to simulate the dynamic operation of the HVAC plant of the apartment, the integration of all subsystems was carried out, starting from the emission until the generation sub-system. This step led to the creation of a dynamic and integrated building-plant model consisting in total of 81 components (Type), all connected according to an input – output logic.

In fact, in Trnsys software each Type can be considered as a “black box”, which processes input data as a function of defined algorithms, starting from user-defined parameters, and produces output data. The task of each Type is to solve simple problems, and their interconnection allows the user to solve the complex problem that is being analyzed.

In the case study shown here, each Type corresponds to a single component of the entire building-plant system. In particular, the model created for the heating plant is synthetically structured as follows:

- Generation + storage sub-systems: natural gas boiler whose operation is governed on the basis of the temperatures measured inside the buffer tank placed downstream;
- Distribution sub-system: three-way diverter and mixing valves able to ensure at each moment the correct flow temperature regulated depending on the outdoor temperature (climate control), variable speed pump, distribution piping from the storage tank to the supply/return manifold and from the latter to radiators;
- Emission subsystem: aluminum radiators;
- Regulation subsystem: individual room PI type able of acting on the flow of heat transfer fluid to the single radiator, with feedback constituted by the actual ambient temperature recorded.

The characterization of all TRNSYS Types used for the plant components has been made from data resulting from the stationary plant design made previously, with the difference that the model created allows us to check the actual operation of the entire and dynamic building-plant system at any variation of all possible internal and external conditions, taking into account each instant the interaction of all the components.

This model represents the highest degree of simulative details with a high number of outputs made available at each time-step (up to about 700 outputs), from the operating temperatures in all components to the unsteady heat balance regulating each component, the cumulative efficiencies of the various sub-systems installations, and the indicator of the overall quality of the designed system.

4.2 Building envelope simplification

As previously mentioned, the complete dynamic model has been subjected to simplifications, in order to test the quality or accuracy of the results of the simplified models, also in relation to the lower work-load required for the latter, during the building retrofit design.

For the building envelope, a simplified protocol already tested by Picco et al. (2013) was adopted, divided into the following steps:

- Step 1 - Simplified construction: reducing the number of constructions to only 7 archetypes reflecting the average transmittance of each type of dispersant surface considered for the whole building (no simplification provided for thermal bridges);
- Step 2 - Removal of external obstructions: Elimination of all the external shading elements modeled;

- Step 3 - Zone lumping: the apartment is reduced to a single thermal zone with constant parameters and internal gains representing mean values of the zones previously considered;
- Step 4 - Simplified transparent surfaces: Modeling only one window for each cardinal direction that considers all of the windows present in that direction;
- Step 5 - Squaring Zone: The "squaring" of the areas of the zones is meant to define a zone as an element composed of only six surfaces making up a box. In order to allow such simplification for the present case the main information to maintain as close as possible to the full model are the dispersant surfaces.

The output of this simplification protocol for the apartment analyzed is reported in Figure 4 and it is called simplification A.

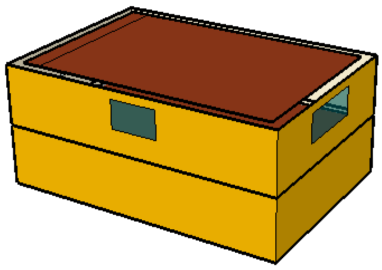

Figure 4 – Simplification protocol (A): Simplified 3D model

4.3 Heating plant simplifications

About the plant, two different macro simplifications were adopted (called B and C):

1) Heat regulation with external energy input (B): This simplification involves the replacement in the detailed model of the component related to the simulation of the building behaviour with one or more Types (depending on the number of zones simulated) constituted by external data files that gives, at each time-step, the ideal thermal useful energy demand of each zone considered.

These data files represent the new external input of the environmental control sub-system, no longer based on the internal temperature of the zones simulated, assumed equal to the set point temperature as a boundary condition for the radiators.

Data files of the ideal energy demand were obtained, as shown later, from previous simulations regarding only the building envelope.

2) Resizing in a single zone (C): the reduction of all zones simulated to a single zone is necessarily accompanied by a new sizing of the plant, in particular of the emission and distribution subsystems:

- The seven radiators considered before were replaced by a single radiator, sized according to the total power requirements of the new single zone;
- The diameter of the distribution network piping from the supply/return manifold to the radiator was increased reaching the dimensions of the piping from the storage tank to the outlet/return manifold, in order to ensure the transport of the proper hot water flux, while the piping length was assumed, both for supply and the return, equal to the outer perimeter of the zone.

5. Case studies and comparison parameters

Thanks to the stationary case, the complete dynamic simulations done for the entire building-plant system, and its simplifications (A), (B), (C), 8 different annual simulations were identified and carried out, summarized in the following table:

Table 1 – Case studies (with * is indicated the most complete and detailed simulation)

CASES		ENVELOPE		
		TERMUS	TRNSYS	
		DETAILED MODE	DETAILED MODE	DETAILED MODE - (A)
HVAC	IDEAL LOADS	1	2	3
	DETAILED MODE	4	5*	/
	DETAILED MODE - (B)	/	6	/
	DETAILED MODE - (C)	/	/	7
	DETAILED M. - (B) - (C)	/	/	8

In particular, the articulation of the simulations is the following:

- Case study 1: a complete stationary energy simulation of the building, through TERMUS software (time-step 1 month), i.e. a stationary simulation only for the building envelope, or, in other words, the determination of ideal loads through a stationary model (ideal loads means that all the thermal efficiencies of the heating plant subsystems are set equal to one);

- Case study 2: a complete dynamic energy simulation of the building system, through TRNSYS software (time-step 1 hour), i.e. a detailed model only for the building envelope, without the integration of all the subsystems of the heating plant (determination of the ideal loads through a complete dynamic model);

- Case study 3: dynamic energy simulation of the simplified building system through TRNSYS software (time-step 1 hour), i.e. Case study 2 + building envelope simplification (A);

These first three simulations, only related to the building envelope have been considered to determine the comparison of the following three parameters:

- Phmax (kW) = Maximum ideal thermal power required by the apartment during the heating season;

- Qh (kWh) = annual ideal thermal energy demand of the whole apartment;

- (Ph, t) = Thermal power curves describing, in addition to the two previous parameters, the distribution of the ideal power required during the entire year of the simulation, as shown in the example in Figure 5 (pay attention that this curve cannot be obtained for Case study 1).

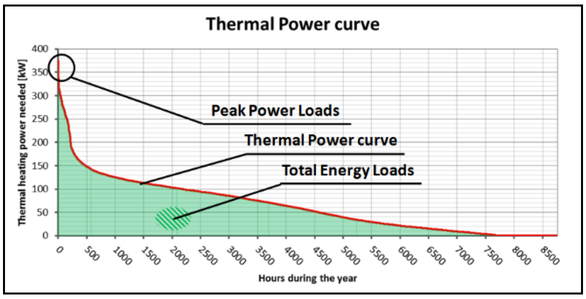

Figure 5 – Example of thermal power curve

Furthermore:

- Case study 4: stationary energy simulation of the entire building-plant system, through TERMUS software (time-step 1 month) = Case study 1 + application of standard efficiency values for all the subsystems of the heating plant;

- Case study 5: dynamic energy simulation of the entire building-plant system, through TRNSYS software (time-step 5 min) = the most complete detailed model.

It should be noted that this is the case study taken as a reference for comparison with the results of all the other cases analyzed, constituting the highest degree of detailed simulation for both the building envelope and the heating plant.

- Case study 6: dynamic energy simulation of the entire building-plant system + Regulation with external energy input, through TRNSYS software (time-step 5 min) = Case study 5 with simplification (B);

- Case study 7: dynamic energy simulation of the entire building-plant system + building envelope simplification + Sizing for single zone, through TRNSYS software (time-step 5 min) = Case study 5 wit simplification (A) and (C);

- Case study 8: dynamic energy simulation of the entire building-plant system + building envelope simplification + Sizing for single zone + Regulation with external energy input , through TRNSYS software (time-step 5 min) = Case study 5 with simplification (A) , (C) and (B);

Due to the high number of available outputs, the comparison has been restricted to the output parameters and curves able to describe the annual operation:

- Phmax (kW) = Maximum useful thermal power required during the heating season, equal to the maximum power introduced by the emission subsystem and by the recovered distribution losses (it has been assumed a recovery rate of 100% of the losses of the distribution subsystem)

- (Ph, t) (kW) = Thermal power curves of the apartment, referring in this case to the annual trend of the useful thermal power introduced in the apartment described in the previous point;

- EPh (kWh) = annual primary energy heating demand;

- ηx = annual average efficiencies of all subsystems of the heating plant and annual average overall performance of the heating plant;

For the last five simulations the annual ideal thermal energy demand Qh is obviously equal to the one resulting from the simulations carried out only for the building envelope (cases 1,2,3, see value of Qh reported in Table 2).

6. Final results

The results of the 8 simulations carried out in absolute values and percentage differences compared to the reference Case study 5 (highest degree of detailed simulation for both the building envelope and the heating plant), are summarized in the following tables and graphs. The workload required to perform each case has been added, in order to evaluate not only the accuracy of the results, but also a rough estimation the time required to obtain them.

Workload, estimated from repeated attempts, has been defined as the time (days) spent to carry out each simulation, considering that all the data needed to characterize the various zones are already available. For dynamic simulations, the time required for the input-output connections of TRNSYS Types has not been considered. In fact, the detailed model has a general scheme and may be applied for a very large number of residential buildings, only changing the components' input data.

Table 2 – Results – absolute values

COMPARISON RESULTS – ABSOLUTE VALUES									
Symbol	U.m.	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7	CASE 8
Timestep	h	744.00	1.00	1.00	744.00	0.08	0.08	0.08	0.08
Ph_max	kW	4.67	7.17	6.25	4.67	9.75	5.04	9.30	6.51
Qh	kWh	8151.25	8243.14	7738.65	8151.25	8243.14	8243.14	7738.65	7738.65
EPh	kWh	8151.25	8243.14	7738.65	9265.67	10049.22	9403.37	9561.60	8863.54
ηe*ηrg	/	1.00	1.00	1.00	0.94	0.90	1.00	0.90	0.99
ηd	/	1.00	1.00	1.00	0.96	1.01	1.00	1.00	1.01
ηs	/	1.00	1.00	1.00	1.00	0.91	0.90	0.90	0.90
ηgn	/	1.00	1.00	1.00	0.97	0.97	0.97	0.97	0.97
ηg	/	1.00	1.00	1.00	0.88	0.82	0.88	0.81	0.87
Workload	days	2.5	3.5	1	3	6	5.5	3.5	3

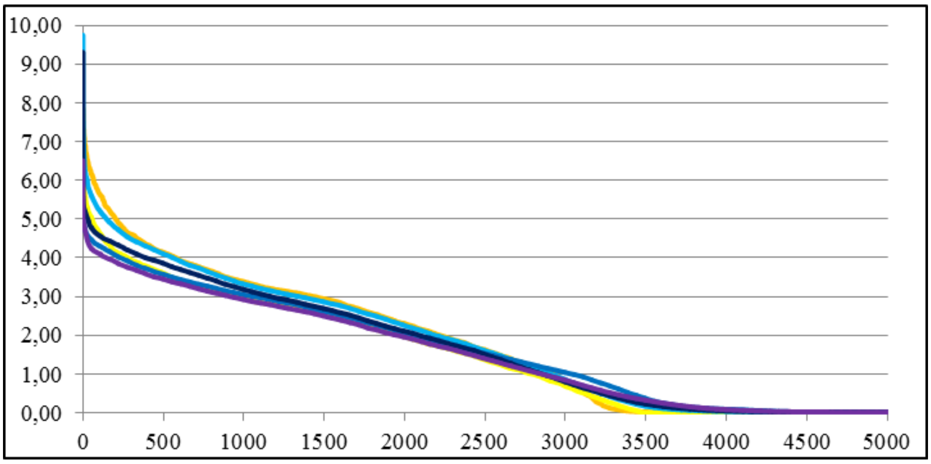

Figure 7 – Results - thermal power curves

Table 3 – Results – Percentage deviations

COMPARISON RESULTS - % DEVIATIONS COMPARED TO CASE 5									
Symbol	U.m.	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7	CASE 8
Ph_max	kW	48%	74%	64%	48%	100%	52%	95%	67%
Qh	kWh	99%	100%	94%	99%	100%	100%	94%	94%
EPh	kWh	/	/	/	92%	100%	94%	95%	88%
ηe*ηrg	/	/	/	/	105%	100%	111%	100%	110%
ηd	/	/	/	/	95%	100%	99%	99%	100%
ηs	/	/	/	/	110%	100%	99%	99%	98%
ηgn	/	/	/	/	100%	100%	100%	100%	100%
ηg	/	/	/	/	107%	100%	107%	99%	106%
Workload	days	42%	58%	17%	50%	100%	92%	58%	50%

It can be stated that:

- The value of the maximum useful thermal power Phmax, introduced in the building to ensure the temperature set point, has a fairly high variation, with peak values higher for cases 5 and 7, i.e. for dynamic simulations where the feedback of the regulation subsystem is constituted by the interior temperature of the simulated zones. However, observing the thermal power curves, it is possible to note that such peak values are required for a number of hours per year absolutely negligible, while the curves indicates the presence of a peak around the mean power of 5.5 kW, however higher to that returned by the first stationary simulation, equal to 4.67 kW.
- Thermal power curves (Ph, t) have a very similar trend. In the central part of the curves, there are constant differences between cases 2-3, 5-7 and 6-8, due to the simplification (A), which underestimates the useful energy requirements of the building envelope. There are small opposite deviations in the intervals near the maximum and minimum power in particular for the cases 5-6 and 7-8, where the simplifications adopted for the plant become more important, going to affect in particular the operation of the emission and regulation sub-systems (simplification B), which are stressed for low and high thermal powers;
- The value of the annual ideal thermal energy demand (Qh) has a maximum variation of 6%. In particular, by adopting for both the detailed stationary and the dynamic simulations the same characterization of zones (notice that thermal bridges on a small building play a very important role and in both simulations are estimated with stationary algorithm), the values of Qh for these simulations are very close. The simplification (A) determines an acceptable underestimation equal to 6%, equal to the difference of the areas under the thermal power curves of the cases 2 and 3.
- The energy efficiencies of the distribution (ηd), storage (ηs) and generation (ηg) sub-systems, for all the dynamic simulations concerning the whole building-plant system (cases 5,6,7,8), are almost constant. They assume quite different values in the stationary simulation (case 4), which does not take into account the possible recovered distribution losses and the storage subsystem.

In particular the efficiency of the distribution network piping for dynamic simulations assumes high values, due to the total recovery of distribution losses and the partial thermal recovery of the energy consumed by the distribution pump.
- Both in the stationary simulation (case 4) and in the dynamic simulations 6 and 8, in which the controller feedback is an external energy data file reporting the ideal heating requirements of the simulated zones, the emission and regulation efficiency (ηe* ηrg) is overestimated compared to cases 5 and 7, where the feedback is more realistically represented by the internal ambient temperature.

As expected, the simplification procedure (B) has a stronger effect on regulation, bringing the plant to provide almost perfectly the ideal energy requirements of the building.
- Finally, the primary energy demand of the building EPh has a fairly limited variability, with an underestimation of up to 12% for case 8, i.e. for the dynamic simulation characterized by the highest degree of simplification. Even the stationary simulation underestimates the EPh value compared to the case 5.
- About the workload, it is possible to note how, compared to a maximum loss of accuracy of 12% of the most simplified case 8, the time required to perform a simplified dynamic simulation of the entire building-plant system is reduced to one half, and becomes equal to the time required to perform a complete stationary simulation (Case 4). However, the latter is not able to ensure benefits that only a dynamic simulation is able to guarantee, such as the full control of the integrated operation of all the heating plant components at any variation of internal and external conditions.

7. Conclusions

The present analysis shows the great potential of dynamic energy simulations during any stage of the integrated design of the entire building-plant system.

The main results are:
- Stationary and dynamic simulations may lead to close global results;

- Results for individual components and subsystems may differ because of the more accurate algorithms and assumptions used during the development of dynamic simulations
- The dynamic simulations are able to provide a number of output far greater than those given by a stationary approach and therefore allow a more precise evaluation of the instationary power loads.
- A simplified dynamic approach provides a complete energy simulation with a very high accuracy and a workload equal or even less that the time necessary to perform a complete stationary simulation.

Finally, it can be stated that rapid but still accurate and integrated dynamic simulations, like the ones shown in this paper, have the potential be the perfect answer to the growing demand, both in terms of quality and low engineering costs, in the residential retrofit design.

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